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An Experimental Study of the Turbulent Development of Rayleigh-Taylor and Richtmyer-Meshkov Instabilities

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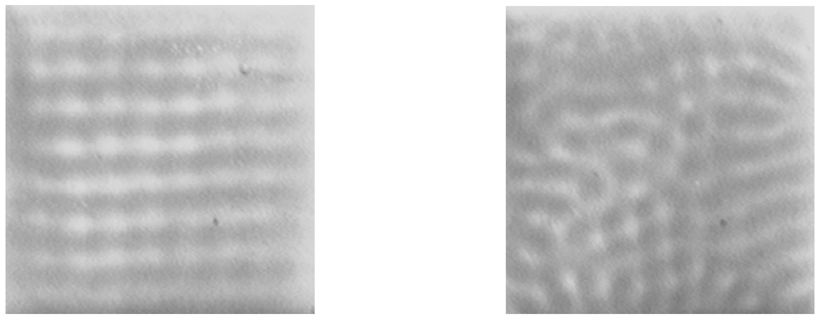
The objective of this three-year research program is to study the development of turbulence in Rayleigh-Taylor (RT) and Richtmyer-Meshkov (RM) instabilities. Incompressible RT and RM instabilities are studied in an apparatus in which a box containing two unequal density liquids is accelerated on a linear rail system either impulsively (by bouncing it off of a spring) to produce RM instability, or at a constant downward rate (using a weight and pulley system) to produce RT instability. These experiments are distinguished from others in the field in that they are initialized with well defined, measurable initial perturbations and are well visualized utilizing planar laser induced fluorescence imaging. New experiments are proposed aimed at generating fully turbulent RM and RT instabilities and quantifying the turbulent development once fully turbulent flows are achieved.

The proposed experiments focus on the development and the subsequent application of techniques to accelerate the production of fully turbulent instabilities and the quantification of the turbulent instabilities once they are achieved. The proposed tasks include: the development of RM and RT experiments utilizing fluid combinations having larger density ratios than those previously used; the development of RM experiments with larger acceleration impulse than that previously used; and the investigation of the multi-mode and three-dimensional instabilities by the development of new techniques for generating short wavelength initial perturbations.

Progress towards fulfilling these goals is currently well on track. Recent results have been obtained on experiments that utilize Faraday resonance for the production of a nearly single-mode three-dimensional perturbation with a short enough wavelength to yield a self-similar instability at late-times. Last year we reported that we can reliably generate Faraday internal waves on the interface in our experimental apparatus by oscillating the tank containing the two fluids in the vertical direction at the proper frequency. This past year we have completed experiments that demonstrate that self similarity is achieved in these experiments utilizing this perturbation. Also, last year we reported preliminary experiments utilizing a new miscible fluid combination, consisting of a new very heavy salt solution and water, that has an Atwood number of approximately 0.5. This past year we have completed experiments showing that this fluid combination is capable of generating a self-similar RT growth when initiated with a planar interface.

Faraday wave initial perturbations

Work on the use of Faraday internal waves as initial perturbations for our RM and RT instability experiments began during the first project year as a feasibility study in which a container filled with our standard working fluids was attached to a hydraulic shaker capable of generating the desired vertical oscillation. The fluids were then oscillated over a range of frequencies and amplitudes to observe the results. To visualize the resulting internal waves, a



(a) (b)

Figure 1. Images of the interfacial patterns generated by Faraday resonance

dense concentration of TiO_2 particles was added to the lower heavy fluid making it opaque. The resulting interface was then illuminated using a floodlight oriented at an oblique angle and the interface was observed from directly above using a CCD camera. Note that in this configuration the light scattered by the heavily seeded bottom fluid is proportional to the inclination angle of the interface. Thus surface waves appear as light or dark regions in the recorded video image. Figure 1 are photographs of two typical surface wave patterns generated by this type of forcing Image (a) was taken soon after surface waves first appear and (b) was taken approximately 10 seconds later. As can be observed here, this type of oscillation produces a nearly single-scale wave form with a square pattern. However, with time the square pattern begins to degrade as the interface develops a more random character. It should be noted that this type of pattern looks very similar the initial perturbation utilized by recent computational studies focused on generating self-similar turbulent Rayleigh-Taylor instability. In these investigations the perturbation spectrum has a sharp short wavelength peak but with finite narrow width.

Experiments utilizing this type of perturbation indeed show the beginnings of what appears to be self-similar turbulence. Figure 2 is a sequence of PLIF images from one of these experiments which shows that the instability begins from a nearly single-mode perturbation but that it quickly develops a more random character by the nonlinear interaction of the slightly nonuniform waves. At the latest times the flow exhibits a very random looking behavior suggesting turbulence. This past year was spent performing similar experiments and extracting quantitative measurements of the spreading rates of this flow. To accomplish this experiments

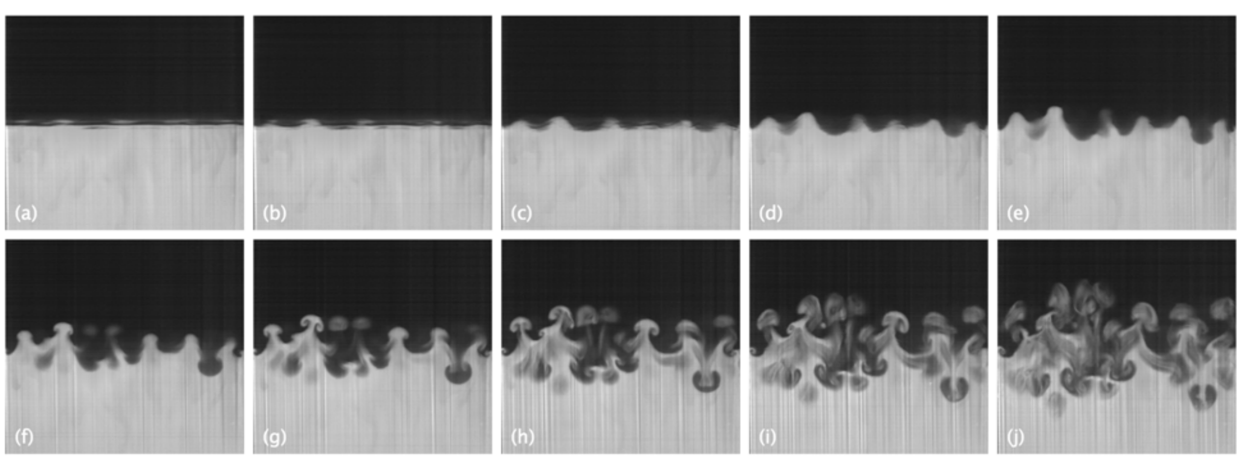


Figure 2. PLIF images from an RT experiment initialized with a Faraday forced initial perturbation.

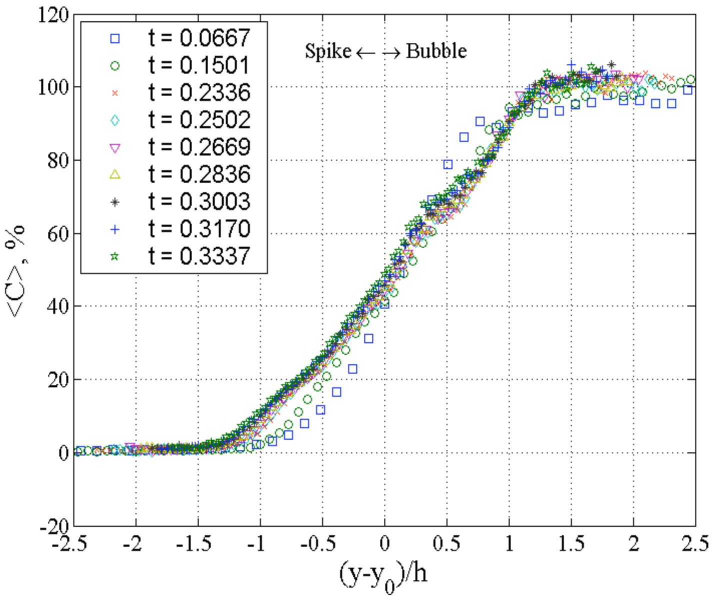


Figure 3. The mean concentration distribution for an ensemble of 10 Rayleigh-Taylor experiments plotted in similarity coordinates showing the collapse of the experimental data.

were performed using backlit photography where the bottom fluid is dyed with a dark opaque dye and a pulsed LED back light is used to illuminate from behind. In this configuration the CCD camera captures images that are functions of the integrated concentration along the line of sight which can be used to extract the true integrated concentration field. Row averaging these measurements then yields concentration measurements averaged in both horizontal directions. If self-similarity is to apply in these experiments one would expect these horizontally averaged measurements to collapse to a single curve using the proper similarity coordinates. Figure 3 is a plot of the average concentration profile for an ensemble of 10 experiments which indeed shows this collapse. In addition, self-similarity suggests that the width of the mixing zone should increase following αAgt^2. Figure 4 is a plot of the locations of the 10% (spike) and 90% (bubble) concentration locations of the horizontally averaged profiles plotted against Agt^2. If self-similar growth is observed one should expect these curves to approach a straight lines at late times in these coordinates. In addition, the slopes of these lines should equal growth constant α. Figure 4 indicates that self-similar growth has been achieved and yields a value of a_b = 0.058 and a_s = 0.102.

New Heavy Liquid Experiments

As mentioned above an important component of the proposed research is the development of RM and RT instability experiments utilizing fluid combinations having larger density ratios than those previously used. Work on this topic began the first project year with a systematic search for suitable liquid combinations. The most important requirements for this combination is that it has a large density difference. However, it is also essential that the fluids be nontoxic, miscible, and that they have relatively low viscosity. Another important desirable property is that both fluids have the same index of refraction in order to allow the use laser sheet diagnostics such as planar laser induced fluorescence (PLIF) or particle image velocimetry (PIV). However this requirement is less important than the others. Through extensive research

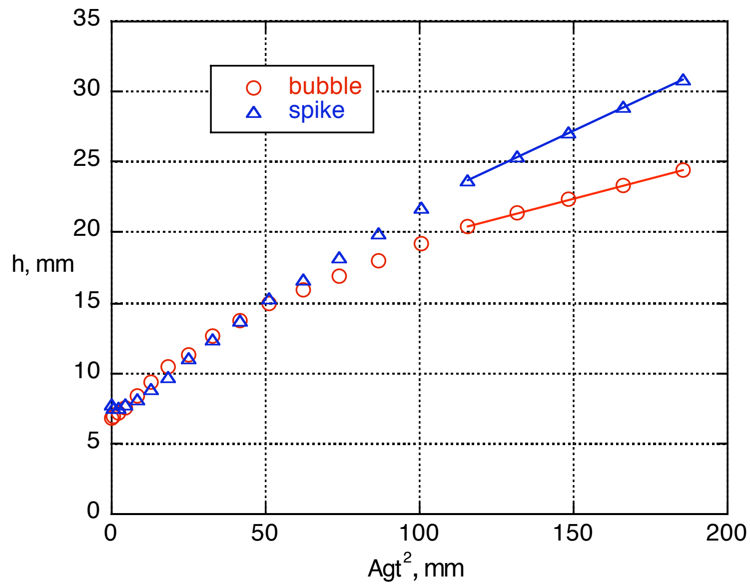


Figure 4. A plot of mix width for the Faraday forced experiments as a function of Agt^2 showing apparent self-similar growth at late time.

we have found that a solution of lithium heteropolytungstates in water yields a very dense (S.G. ≈ 3) nontoxic liquid with low viscosity which when combined with isopropyl alcohol provides a suitable miscible fluid combination for use in our RM and RT experiments. Unfortunately these two fluids do not have the same refractive index. Therefore backlit photography must be used instead of PLIF to visualize this flow.

Preliminary experiments using this liquid combination have produced instabilities much more prone to becoming turbulent. More recently, we have found that we can produce a fully turbulent RT instability initiated with a nominally flat interface. It should be noted that in previous experiments using smaller Atwood number fluid combinations ($A \approx 0.2$) instabilities

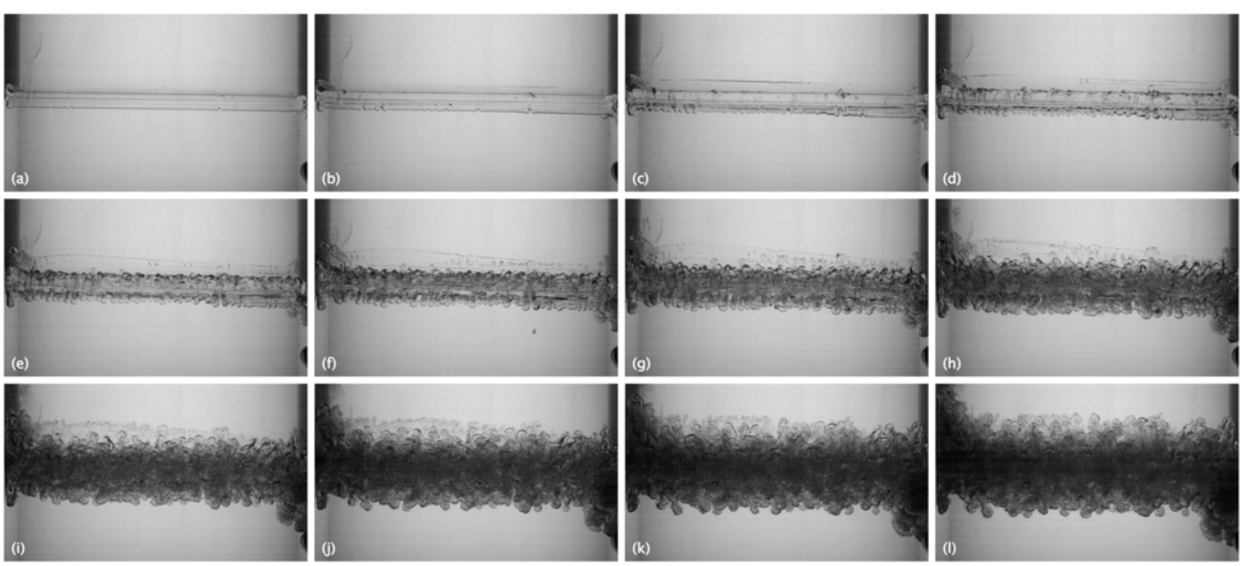


Figure 5. An RT experiment using the heavy fluid combination initiated with a flat interface.

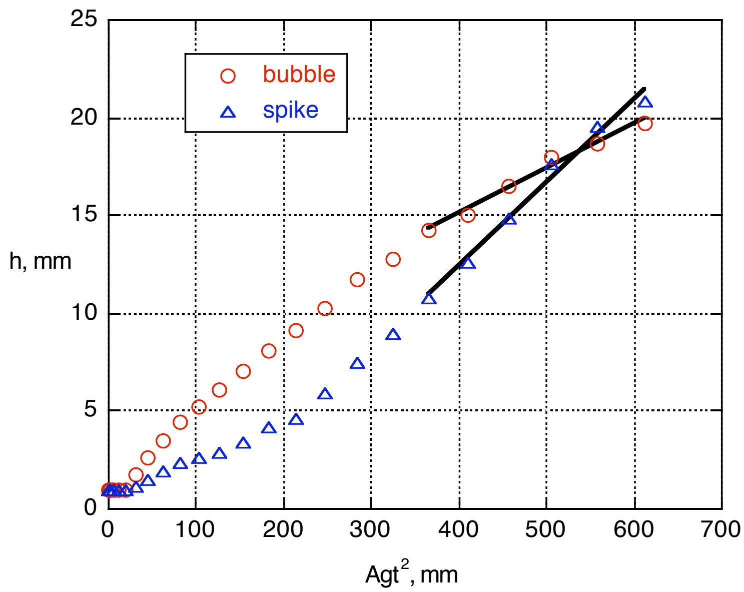


Figure 6. A plot of mix width for the heavy liquid experiments as a function of Agt^2 showing apparent self-similar growth at late time.

initiated with flat interfaces resulted in no observable instability growth. However, recent experiments at large Atwood number ($A = 0.57$) clearly show the development of turbulent RT growth apparently evolving from very small length scales. Figure 5 shows an image sequence taken from one of these experiments. An interesting aspect of these experiments is that if one assumes the perturbations that first appear in frame (c) grow following linear stability theory from an initial perturbation of unmeasurable size, one finds that the amplitude of this initial perturbation must be of the order of the molecular spacing of water. This suggests that this instability is initiated from molecular motion, i.e., thermal noise. Measurements of the growth of the mix width in these experiments versus time indicate self similar growth as shown in figure 6, with alpha measurements of a_b = 0.023 and a_s = 0.043.

Financial Information

Spending on this grant is on track. We have benefited slightly by the fact that the Department of Aerospace and Mechanical Engineering has contributed to the salaries of two of the graduate students working on this grant by employing them as 1/4 time teaching assistants. This has allowed us to increase slightly the number participants which in turn has accelerated the work schedule. Large purchases include the lithium heteropolytungstates solutions used in the large Atwood number experiments. In addition a laboratory rotary evaporator system was purchased to aid in the recovery of the heavy liquid solution. There were four people supported on this grant, and their names and contributed effort are listed below.

Project participants		**Time supported by this grant**
Postdoc:	Oleg Likhatchev	25%
Graduate Students:	Michael Roberts	37.5%
	David Olson	37.5%
Faculty:	Jeffrey Jacobs	11%

Theses

David Olson, “Experimental Study of Rayleigh-Taylor Instability with Complex Initial Perturbations,” MS awarded May 2006.

Publications

Chapman, P.R. and Jacobs, J.W. "Experiments on the three-dimensional incompressible Richtmyer-Meshkov instability" *Phys. Fluids*.**18**, 074101, 2006.

Presentations/Absracts

M. Roberts, and J. Jacobs, “Experiments on the Rayleigh-Taylor and Richtmyer-Meshkov instabilities utilizing a large Atwood number miscible liquid combination,” presented at the 58th Annual meeting of the APS/DFD, Chicago IL, November 2005.

D. Olson and J. Jacobs, “Experimental study of the Rayleigh-Taylor instability initiated with a complex, short-wavelength initial perturbation,” presented at the 58th Annual meeting of the APS/DFD, Chicago IL, November 2005.

Invited Presentations

Progress on the Experimental Study of Richtmyer-Meshkov Instability, presented at Lawrence Livermore National Laboratory, April 2005

Experiments on the Rayleigh-Taylor and Richtmyer-Meshkov Instabilities, presented at the JASON summer study workshop, La Jolla, CA, July 2005